A REVIEW OF MANGANIN GAUGE TECHNOLOGY FOR MEASUREMENTS IN THE GIGAPASCAL RANGE

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G. YIANNAKOPOULOS

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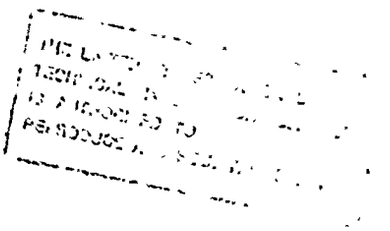

A REVIEW OF MANGANIN GAUGE TECHNOLOGY FOR MEASUREMENTS IN THE GIGAPASCAL RANGE

G. Yiannakopoulos

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ABSTRACT

This report provides a comprehensive review of manganin gauge technology, including aspects of gauge design and construction, recording instrumentation and experimental techniques, and the interpretation of experimental results. Manganin gauges are shown to be capable of resolving to the order of 10 nanosecond pulses in the stress range 1 to 40 GPa.

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A REVIEW OF MAGANIN GAUGE TECHNOLOGY FOR MEASUREMENTS IN THE GIGAPASCAL RANGE*

1. INTRODUCTION

There is a requirement at MRL, particularly from the Explosives Division, to establish a capability to measure dynamic stresses in the 1 to 40 GPa range to study the behaviour of shock loaded solids. One such example involves the study of shock induced conduction of polymers. Shock induced conduction is the property where materials that are normally insulators become conductive when subjected to a shock wave (Davison and Graham, 1979, 336-340). The transition from insulator to conductor takes place in a few nanoseconds and involves stresses in the GPa range (Graham, 1980, p. 149). This property has been utilised at MRL for a rapidly actuating electrical switch for slapper detonators (Richardson and Jones, 1986). The switch consists of a microtransmission stripline with the polymer polyimide sandwiched between two copper strips, (overall thickness 40 μm). By impacting an explosively driven flyer plate onto the microtransmission stripline the polyimide becomes conductive closing a circuit. In this case the measurement of the stress-time history of the polyimide would provide an understanding of shock wave propagation and would enable a better switch design.

Other examples include studies in spallation (Yellup 1984), the synthesis of explosives (Spear and Wilson, 1984) and the jet initiation of solid explosives (Chick and MacIntyre, 1985). In spallation studies dynamic stress measurements would provide spall strengths of materials (Rosenberg, Mayseless, Partom and Betser, 1985). In the synthesis of explosives the measurement of detonation pressure would provide a comparison with estimates made from the molecular structure of the explosive composition (Kamlet and Jacobs 1968). Furthermore, reaction rates can be inferred by using Lagrangian gauges which involve embedding several manganin gauges in the material for the measurement of detonation pressure at several locations (Tarver et al, 1983). In studies

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* Refer to Appendix 1 on the terminology used in the literature on shock waves in condensed matter.

involving the jet initiation of explosives, divergent shock waves can be studied (Titov, Karakhanov and Bordzilovsky 1985; Larson and Stout 1987). This last example however will require further gauge development because the measurement is no longer in one dimension.

Currently our present instrumentation facilities at MRL enable the measurement of the velocity of detonation (Campanella, Wolfson and Box, 1987), and the study of shock wave material response through the use of either high speed photography (Wolfson, 1986) or flash X-ray instrumentation (Chick and Macintyre, 1985). A VISAR is currently being installed. This is an optical means of determining the free surface motion of a sample or the motion between the sample and an optically clear material. At this stage we do not have the capability to measure directly stresses in the GPa range.

This report reviews the literature on the use of manganin gauges for the measurement of dynamic plane stress waves. The aim was to make an appraisal of the effort involved in establishing this capability.

Other gauges such as the quartz, ytterbium and carbon gauges can be used for stress measurements, however, these are not as versatile. The polyvinylidene fluoride (PVF_2) polymer gauge, which has a piezoelectric film sensing element (Figures 1-2) has been reviewed elsewhere (Reed, 1987). This review indicated that the polymer gauge is easier to instrument, has nanosecond resolution and has linear response even upon unloading from reflected waves. However, this gauge still presents a number of disadvantages. It has not been as well studied as the manganin gauge and is still under development. Comparisons of stress records from the literature would be very limited. (Note that the stress range for PVF_2 gauges has been recently extended to 46 GPa, R.A. Graham, personal communication, 3 August 1988).

2. BACKGROUND MATERIAL ON MANGANIN GAUGES

Manganin gauges are an important tool for the direct measurement of high dynamic stresses. Measurements of stresses as high as 125 GPa have been reported (De Carli et al, 1976). They have been used extensively for over 25 years in the UK (Burrows et al, 1976), USA (Erickson et al, 1981b) and USSR (Kanel, Vakhitova and Dremin, 1978). More recently, an enormous amount of literature has been produced from Israel by Z. Rosenberg and co-workers. Other countries that have reported on their usage include Canada (Jacques, Belanger and Matte, 1985), China (Ding, 1976, p. 797-8) and Japan (Yasumoto, Kondo and Sawaoka, 1980).

2.1 Composition and properties of manganin alloy

Manganin is a generic term for alloys consisting of 83 to 87% copper, 12 to 13% manganese and 0 to 4% nickel, (Metals Handbook, 1978, vol. 3, p. 643-644). The composition of the manganin gauge is usually 84% copper, 12% manganese and 4% nickel. Manganin alloy has a large positive piezoresistive coefficient, from 38 to 48 $\mu\Omega$.cm and a low temperature resistivity coefficient, less than 15 ppm/°C, (Metals Handbook, 1978, vol 6, p. 643).

Table 1 lists some dynamic constants that have been reported.

2.2 Principle of operation

The low temperature resistivity coefficient and the large piezoresistance coefficient of manganin alloy mean that, when it is dynamically compressed, the change in resistance due to the induced stress is much larger than the accompanying change due to temperature (Fuller and Price, 1964, p. 752). From the electrical point of view, the resistance change from a short piece of manganin alloy is large enough to be measured. From the mechanical point of view, a manganin element may be made very thin and does not perturb the propagation of the shock wave and material flow. These qualities make manganin alloy a suitable material for use as a transducer for dynamic stress measurements.

Stress measurements are conducted by monitoring the resistance change across the manganin alloy caused by the dynamic load (Figure 3). This change is due to both the variation in dimensions and resistivity. At very high stresses (GPa region) involving uniaxial strain, the changes in the gauge dimensions are small so that the change in resistance is predominantly caused by the variation in resistivity (Chen, Gupta and Miles 1984, p. 3991). Table 2 lists some of the major works that have contributed to the understanding of the manganin gauge response.

2.3 Configurations

The gauge has been used in a number of configurations. Variations occur in the electrical element, bonding agent, insulator material, number of terminal leads, and manufacturing processing.

2.3.1 The electrical element

The electrical element refers to the manganin alloy which is the sensing element (figure 3). The geometry of the element may be wire or foil with resistances ranging between 0.030 and 350 ohm (Table 3). Figures 4 to 18 illustrate the different types of manganin gauges reported in the literature. The choice of the type used is based upon the stress levels to be measured. Gauges with resistances less than 0.1 ohm will be referred to as low impedance gauges.

The wire configuration (Figure 4) is the oldest type used (Fuller and Price 1964, p. 751-753; Bernstein and Keough, 1964, p. 1471), and the gauge is rarely used in this configuration. Note that under conditions involving raiefaction waves where the gauge experiences unloading this type has consiberably less hysteresis than the foil or strip type (Partom, Yaziv and Rosenberg 1981, pp. 4611-4612).

The foil element may be either a grid (Figures 5 to 8) or a strip (Figures 9 to 12) and is used in applications involving uniaxial strain in the 1 to 15 GPa stress range, where the range is limited by the insulation layer (section 2.3.3). The thinnest grid element (5 μm) can be used in applications involving nanosecond resolution (Rosenberg and Bless 1986, p. 1384).

The strip element has been constructed to measure detonation pressure (Vantine et al, 1980a, p. 117). Because it is thicker than the foil type, it has greater mechanical strength and consequently has a comparatively longer lifespan in this environment. Therefore longer stress-time profiles can be obtained.

The dimensions of the gauge vary and the size selected depends on the particular application, refer to Micro-Measurements (1988), part A, pp. 84-85, and Dynasen Inc. (1982) specifications for commercial gauges. A commonly used size for the high impedance gauges is 3 mm x 3 mm in the sensing area with a thickness from 5 μm to 25 μm (Figure 8). The low impedance gauges have active elements of 1.5 x 6.0 mm with a thickness of 25 μm (Figure 10). However variations occur (Figure 12) and smaller sizes can be constructed to meet the requirements of a given application (Figure 13).

In special applications other gauge geometries have been constructed. For example, in measurements involving "sweeping loads", a "T" shaped gauge (Figures 14 to 15) has been used (Duggin and Butler 1970, p. 623). In diverging shock wave measurements where gauge deformation occurs, a constantan gauge (Figures 16 to 18) has been used together with manganin. The constantan element measures strain only and enables strain compensation (Rosenberg, Yaziv and Partom, 1980b). This philosophy has also been used in a gauge consisting of constantan interlaced with manganin (Figure 18).

For stress levels around 1 GPa, signal levels from manganin gauges are low. In these applications sensing elements consisting of other materials may need to be used. Two commonly used materials are ytterbium (Figure 19) and carbon (Figure 20). These gauges are instrumented in the same manner as the manganin gauge.

2.3.2 The bonding agent

The bonding agent is an adhesive layer between the sensing element and insulation and the insulation and specimen (Figures 21, 22). Typically it consists of an epoxy with a known Hugoniot shock response curve. Early workers commonly used Armstrong Products Inc. epoxy C-7/A (Keough and Wong 1970, p. 3613, table II). Although many epoxy systems have been studied, information from the literature is usually not detailed enough to enable an identification of the type used.

Table 4 lists epoxies that have been adequately specified. Note also that the epoxy also acts as an electrical insulator.

In the low impedance gauges, fluoroethylene propylene (FEP) type C (i.e. chemically treated to enhance bondability) has been used as a bonding agent between the gauge and insulation (Erickson et al, 1979, 21-3). Bonding is achieved by melting the FEP.

2.3.3 The insulation

The insulation is an electrically non-conducting material which isolates the gauge from a conducting environment (Figure 21). Insulation materials include polyimide, polytetrafluoroethylene (PTFE), glass fibre reinforced plastic and mica. The insulation may be applied on one side of the gauge or on both sides. Like the epoxy system the insulator must also have a known Hugoniot shock response curve. Some common insulators are listed in Table 5.

The type of insulation used depends on the application. For a gauge in a conducting environment where the stress to be measured is beyond the shock induced threshold pressure of the insulator, a conductive path will be created which shunts the gauge. For example polyimide, which is the most commonly used insulator, becomes conductive at 9 GPa (Graham 1980, p. 149). This problem can be overcome by using insulators that have a high shock induced threshold pressure. Another approach is to use a gauge with a resistance several orders of magnitude lower than the insulation (Vantine et al, 1980a, p. 118). Shunt conductivity failure has been studied for the 50 ohm gauges by comparing the gauge to an open grid with a 50 ohm resistor connected in parallel to the open grid (Ginsberg, Anderson and Wackerle, 1981, p. 5).

2.3.4 Number of terminal leads

The number of leads from the gauge can be either 2 (Figures 5 to 8) or 4 (Figures 9 to 13). The 4 lead configuration has 2 input and 2 output leads and can be single-ended, where all leads emerge from one side, or double-ended H shaped (Vantine et al, 1980a). The 4 lead configuration is used in the low impedance gauge and reduces changes in lead resistance due to stretching (Erickson et al 1979, 21-1). Refer to Muri, Curran, Petersen and Crewdson (1974) p. 72, for a further discussion.

2.4 Gauge placement

The placement of the gauge can be either "in situ", where the gauge is inserted in the material or "back surface", where the gauge is placed in contact with the sample.

2.4.1 "In situ" configuration

The "in situ" configuration (Figures 23 to 25), also called in-material, provides measurements of material bulk properties such as the dynamic yield stress (Rosenberg, Partom and Yaziv, 1984) and longitudinal sound velocity (Rosenberg and Meybar, 1983). The Hugoniot curve of a material can be measured through several impact experiments (Rosenberg, Meybar and Yaziv, 1981). Dynamic phase transitions can also be studied (Rosenberg, Partom and Yaziv, 1980). Detonation measurements involve several gauges placed within the explosive (Ginsberg, Anderson and Wackerle, 1981).

The gauges can be placed in the material laterally or longitudinally (Rosenberg, Partom and Yaziv, 1981, p. 755. Gupta and Gupta, 1987, p. 2604). The gauge is normally used in the longitudinal configuration (Figures 23 to 24) and records longitudinal stresses. Gauges in the lateral (or transverse) configuration (Figure 25), which is a recent development, record lateral stresses.

2.4.2 Back surface configuration

The back surface configuration (Figures 26, 27) is used to measure the wave profile. Applications include uses in the study of spallation (Bless, Yaziv and Rosenberg, 1985), the measurement of rarefaction waves (Rosenberg, 1986) and the study of shock wave evolution (Rosenberg and Bless, 1986).

2.5 Fabrication

Manganin gauges are fabricated from shunt grade manganin alloy. Shunt grade refers to a manganin alloy composition consisting of 85% Cu, 10% Mn and 4% Ni (Metals Handbook, 1978, Vol 3, pp 643-644). This grade is relatively more insensitive to temperature changes. Table 6 lists the various sources of manganin alloy reported in the literature.

Manganin alloy can be annealed or nonannealed. Annealing increases the resistance change of the gauge for a given pressure therefore improving the output voltage signal (Charest and Lynch, 1985; Rosenberg and Charest 1986, p. 2643).

2.5.1 Wire gauges

Wire elements are typically fabricated by first flattening the manganin wire, then soldering copper leads (foil strips) and bonding insulation sheets on each side (Burrows et al 1976, p. 626). Fabrication details of the wire gauges are given in Keough (1968), section III.

2.5.2 Foil gauges

Foil gauges are made by standard photoplating and etching techniques. Details of the fabrication of the low impedance gauges are given by Erickson et al (1979).

2.6 Suppliers of manganin gauges

The major manufacturers for the gauges are Dynasen (Dynasen Inc. 1982) and Micro-measurements Group (Micro-Measurements 1988), both located in USA. Research establishments in countries such as the UK (Burrows et al, 1976), China (Ding, 1985), USSR (Kanel, Vakhitova and Dremin, 1978) construct their own gauges. The cost of the gauge usually depends on the length of the gauge leads.

3. CALIBRATION

Due to the ancillary equipment required, the calibration of the manganin gauges presents the most formidable problem in their use. This is a problem with all the tranducers used in shock wave experiments.

Because the gauge is destroyed in each experiment, calibration is achieved by calibrating a sample number from a batch. If the gauge configuration is chosen so that it corresponds to one in the published literature, then calibration of the gauges is not necessary.

The calibration of manganin gauges can be performed either dynamically or quasistatically.

3.1 Dynamic calibration

Dynamic calibration is the conventional method of calibrating the gauges. It is accomplished as follows :

(a) A flyer plate is accelerated to hypervelocity.

(b) The flyer plate impacts onto a target.

(c) Using the shock impedance matching technique (Appendix 2), the stress resulting from plate impact is determined.

(d) Calibration is completed with the determination of the piezoresistance coefficient K (Appendix 3, Eq 1).

Note that K is not a universal constant. Calibration experiments are needed to determine the value of K for a particular gauge configuration (Graham

and Asay, 1978, p. 377). The problems with dynamic calibration are the following:

(a) The generation of a plane shock wave is difficult to achieve. The conventional methods of generation have been the subject of many reviews (Duvall and Fowles, 1963, p. 223-230; Fowles, 1973, pp. 423-436; Graham and Asay, 1978, pp. 357-362). Commonly used techniques include the explosive lens, the mousetrap and the use of gas guns.

(b) The impact velocity must be measured accurately, typically to 0.5% (Oved, Luttack and Rosenberg, 1978, p. 86).

(c) The planarity of the shock wave needs to be within a small tolerance, typically 1 mrad (Oved, Luttack and Rosenberg 1978, p. 86).

3.2 Quasistatic calibration

Calibration of the gauges through shock experiments is a time consuming and expensive procedure. To determine a calibration curve many shots must be fired; up to 60 experiments is typical (Rosenberg, Yaziv and Partom 1980, p. 3704). Much research has been devoted to simplifying the technique. One method which shows promise is the quasistatic calibration (Rosenberg, Partom and Keren, 1983; Partom, Rosenberg and Keren, 1984; Chen, Gupta and Miles, 1984). This involves the determination of a calibration curve through the application of high static pressures on the gauge using a hydrostatic press. From a mathematical model of the gauge, the calibration curve can be related to the dynamic pressure piezoresistance coefficient (Appendix 3). This technique is limited to uniaxial stress conditions and low stresses (0.75 GPa).

The quasistatic method of calibration can be used in preliminary studies to develop the installation procedure of the gauge, particularly the bonding agent thickness. This involves the mounting of the gauge in an anvil. The assembly is then continuously compressed by a hydrostatic press such as an Instron while the output resistance is recorded (Rosenberg, Partom and Keren, 1983). A comparison can be made with the published literature confirming whether a successful bond has been made.

4. INSTRUMENTATION

4.1 Power supply

The gauge is used in a wheatstone bridge configuration. A high excitation current is required for a high output signal. A pulsed power supply is used to prevent the melting of the gauge (Williams 1968, p. 15). The power supply can be either a constant voltage or constant current supply depending on the manner the bridge is

powered. The constant voltage power supply is used for pressure ranges 1-15 GPa, whereas the constant current supply is used for higher pressure ranges. The advantage of the constant current supply is that the wheatstone bridge has a greater linear range (Daly, Riley and McConnell, 1985, p. 131-139), but more importantly in higher pressure applications, avoids gauge shunting due to the insulation layer becoming conductive (Vantine et al, 1980a, p. 117).

Power supplies are available commercially from Dynasen Inc. and K-Tech Corp. Alternatively, the literature provides sufficient detail for power supplies to be constructed in-house. A list of appropriate references is shown in Table 7.

4.2 Gauge installation

Installation techniques are similar to strain gauge mounting procedures (Steele and Douglas 1974, p. 18-19). However stringent techniques are required to bond the gauge on the specimen and involve:

(a) The use of air evacuated epoxy (Rosenberg Yaziv and Partom, 1980a p. 3703) as air bubbles lead to erroneous results. Preheating the epoxy overcomes this problem (Keough, 1968, p. 34-36; Wackerle, Johnson and Halleck, 1975, p. 20).

(b) Ensuring that the electrical insulation of the gauge and copper leads are adequate to prevent premature shorting (Fowles 1973, p. 470). This is usually done by bonding a layer of mica or Mylar to the gauge and leads.

(c) Thorough cleaning of the gauges (Steele and Douglas 1974, p 18).

(d) The use of special soldering techniques such as indium soldering may be required to attach the connectors to the gauge leads (Oved, Luttack and Rosenberg, 1978, p. 87).

4.3 Data recording system

4.3.1 Signal levels

Wire elements with resistances of about 1 ohm produce signal levels of 20 to 100 mV/GPa (Graham and Asay, 1978, p. 376). Foils with resistances of about 50 ohms produce higher signals and consequently are easier to instrument. Annealed gauges produce even higher output signals.

In the range of 1 to 15 GPa, expected voltage output levels lie between 20 mV and 2.0 V (Graham and Asay, 1978, p. 376). If peak values are required, neither amplification nor attenuation will be needed. However amplification is always used to resolve the stress related component of the output signal.

The low impedance gauges produce signals of the order of 1 V (Vantine et al, 1980a, p. 117).

4.3.2 Recording instrumentation

Details on recording instrumentation techniques are given by Keough (1968), pp. 41-59. The recording instrumentation depends on the measurements required. Differential recording mode is needed to separate the stress signal from the voltage supplied to the gauge.

4.4 Data reduction and Analysis

4.4.1 Data reduction procedure

Let V_o be defined as the voltage supplied by the power supply δV, the change in voltage caused by the induced stress, R_g the initial resistance of the gauge and δR the change in resistance across the gauge.

The data reduction procedure involves the following (Keough 1968, p. 61-71; Wackerle, Johnson and Halleck 1975, p. 21-22) :

(a) The accurate measurement of the ratio $\delta V/V_o$.

(b) The derivation of a function relating $\delta V/V_o$ to $\delta R/R_g$. This expression depends on the particular electrical circuit used (Keough 1968, pp 61-71; Rice 1970; Ovid, Luttwak and Rosenberg, 1978, pp 87-88; Jacques, Belanger and Matte, 1985, pp 28-34).

(c) The relation between $\delta R/R_g$ and the stress on the manganin gauge. This is obtained empirically from calibration experiments (Erickson et al, 1981b, p. 3-4).

From the literature, only one reference contained a description of software needed for data reduction (Wackerle, Johnson and Halleck, 1975, program GANAL). However a good summary exists which outlines the requirements of the software (Erickson et al, 1981b).

4.4.2 Corrections for gauge nonlinearity

Corrections need to be made to the records for the following effects (Figure 28):

(a) **Gauge factor nonlinearity.**

This is accomplished by deriving from calibration experiments an expression relating stress to a polynomial (usually third degree) of $\delta R/R_g$ (Lee, 1973; Rosenberg Yaziv and Partom 1980a; Erickson et al,

1981b). Refer to Figure 28 for a schematic representation of the corrections involved.

(b) **Gauge hysterises upon unloading.**

Corrections are also empirical and are derived from calibration experiments. (Steinberg and Banner, 1979; Vantine et al, 1980b; Erickson et al, 1981b). One technique involves modifying the expression relating $\delta R/R_o$ and stress (Vantine et al, 1980a).

4.4.3 Other types of corrections

For flyer plate impacts involving a small tilt in the flyer plate, tilt corrections are required. This involves iterative numerical methods.

For measurements in conductive environments, corrections may need to be performed electrically such as when the gauge is placed between a conductive flyer plate and conductive target material (Rosenberg, Erez and Partom, 1983). In this case a voltage is induced on the gauge due to the relative motion between the conductive flyer plate and target material. Refer to Figure 29 for an experimental layout and correction circuitry.

Another example of measurements in conductive environments involves measurements in soil. A technique has been developed which minimises inductive pick up (Figure 30).

4.4.4 Interpretation of results

Each application presents a different set of problems. An understanding of material response due to shock loading and shock wave propagation is required. Many references exist that develop these subjects from first principles. Refer to table 8 for a list of some important reviews. A comprehensive description of the literature prior to 1978 can be found in Davidson and Graham (1978), pp. 259-261.

To illustrate the type of interpretation that is required of the results consider Figures 31 to 35 which show the stress profiles from plane impact experiments. Figures 31 to 33 can be interpreted by considering the mechanical properties of the materials. In ductile materials such as aluminium, the rarefaction wave, emanating from the back-surface, causes plastic deformation (Figure 31). However, in brittle materials such as Coors Porcelain alumina AD 85, where there is no plastic deformation, the material fails abruptly (Figure 32). In materials such as potassium chloride (Figure 33), dynamic phase transitions occur and the stress profile is considerably more complex.

The last two examples (Figures 34 and 35) can be interpreted by considering shock wave propagation. In the first of these examples, a shock wave propagates through the copper and is reflected at the copper and aluminium interface. Since aluminium has a lower shock impedance than copper, the

reflection caused at the interface is a rarefaction. The complex step pattern of the stress profile can be interpreted through shock reflection at interfaces.

The last example (Figure 35) illustrates shock propagation in a long rod. The duration of the shock wave is related to the length of the rod. The longer the rod, the longer it will take for the rarefaction to emanate and to cancel the shock. The frequency of the oscillations that appear is also dependent on the length of the rod.

A powerful tool in the analysis of the stress profiles in materials is the distance-time plot. It involves ray tracing of compression and rarefaction waves at material interfaces. The reasoning behind this technique is based on the "method of characteristics". This method involves modelling the shock wave by the wave equation and reducing the wave equation, which is a partial differential equation, to a first order differential equation. Qualitative information about the propagation of the wave in the material can be obtained by considering surfaces in space-time across which the material properties have discontinuities. A summary can be found in Murri (1974), p. 40-41. A thorough presentation can be found in Chou and Hopkins, 1972, Ch. 6, pp. 283-362.

This method leads to powerful insights about material behaviour because the material response can be correlated to the shock wave propagation in the material (Figure 36). Examples of this correlation can be found in the literature for the calibration of manganin gauges (Keough, 1968, p. 85-93), the study of the release history of aluminium (Yaziv, Rosenberg and Partom, 1980, p. 2244) and for spallation studies in polycrystalline ceramics (Bless, Yaziv and Rosenberg, 1985, p. 424).

All applications require an understanding of shock-induced conduction and shock impedance mismatching of materials. Furthermore, consideration has to be given to the dimensions of the materials. For example if flyer plate impacts are studied with the flyer plate diameter to thickness ratio less than 3, radial rarefaction waves are created (Fowles et al, 1970, p. 984). A discussion can be found in Stevens and Jones (1972).

A useful analysis on the response of polycrystalline materials to shock loading can be found in the study of Lithium Fluoride by Gupta, Duvall and Fowles (1974).

4.5 Calibration facilities and instrumentation

Figure 37 shows a schematic of the instrumentation required for dynamic calibration of the piezoresistance gauges. The following equipment is required:

(a) **A plane shock wave generator.**

The most commonly used techniques for generating plane shock waves are:

(i) explosive generators (Duvall and Fowles, 1963, pp. 223-233; Fowles, 1972, pp. 428-33; Graham and Asay, 1978, pp. 357-8);

(ii) gas guns (Graham and Asay, 1978, pp. 358-60; Fowles et al, 1970; Porat and Gvishi, 1980);

(iii) exploding foils (Fortov, 1982, p. 805; Richardson, Northeast and Ryan 1988);

(b) **Instrumentation for the velocity measurement of the flyer plate.**

Measurements are commonly made by velocity pins (Ingram, 1965; Fowles et al, 1970, pp. 991-2; Oved, Luttack and Rosenberg, 1978, p. 86). Interferometric methods such as VISAR (Barker, 1983), ORVIS (Bloomquist and Sheffield, 1983) or Fabry-Perot (McMillan et al, 1988) have also been used. For subnanosecond pin switching times, special pins are required (Graham, 1980, p. 148).

(c) **Instrumentation to determine the tilt of the flyer plate.**

This is commonly performed by tilt pins (Wackerle, Johnson and Halleck, 1975, p. 2-6; Fowles et al, 1970, pp. 991-2) which are the same as the velocity pins.

5. TIME RESOLUTION OF THE RECORDING SYSTEM

In some applications the overall recording system will need to have a time resolution of 1 ns signal risetime. To date the greatest time resolution reported in shock waves in condensed matter has been 300 ps (Sheffield, Bloomquist and Tarver, 1984, p. 3835). This involved the measurement of particle velocity using a velocity interferometric technique. Shock velocity measurements with subnanosecond resolution have also been reported (Mitchell and Nellis, 1981).

5.1 Mechanical considerations

Table 9 lists the time resolution of the manganin gauge packages reported in various publications. Note that the time resolution depends on the location of the gauge (back surface or "in situ"), on the shock impedance of the manganin/bonding agent/insulator, and on the recording system response time.

5.1.1 Shock wave transit time

The back surface configuration provides the greatest time resolution because it reduces shock impedance mismatching. In the case of the "in situ" configuration, because the gauge must be insulated on both sides, the shock wave has to traverse several layers of materials with different shock impedances. In the back surface case, with insulation on one side, the number of layers are effectively halved.

Greatest resolution can be obtained by minimising the thickness of the manganin/bonding agent/insulation, and matching the shock impedances of the bonding agent, insulation and test material as closely as possible. The bonding agent thickness can be minimised by using a low viscosity epoxy such as Eastman 910, and by applying pressure to the bond (Rosenberg, 1988, p. 544). Shock wave signal transit times in manganin gauges have been considered by Williams (1968), p. 12. The discussion by Hayes (1981) pp. 601-603, for the electromagnetic velocity gauge, which is also a foil type gauge, is also useful.

5.1.2 Material strength and viscosity

For shock stresses below 100 GPa the strength and viscosity of the material are significant because the shock wave rise time is finite (a few ns) and during this time the stress is unsteady (Swegle and Grady, 1985). The material must be thick enough to allow sufficient time for the shock wave to reach steady state conditions. If steady state conditions are not achieved, the results cannot be interpreted with the Rankine-Hugoniot conservation equations (Fowles and Williams, 1970, pp. 360-361). Instead, the Lagrangian formulation must be used (Seaman, 1974) where the material is used as a frame of reference rather than the laboratory (Eulerian reference frame).

5.1.3 Tilt

The tilt of the shock front also affects the time response of the overall system and must be minimised so as to achieve the greatest shock planarity (Duvall and Fowles, 1963, pp. 229-230). This problem can also be overcome by minimising the area of the sensing element of the gauge.

5.2 Electrical considerations

There are two problems, signal degradation in the electrical transmission and the response of the recording instrumentation.

5.2.1 Electrical transmission

Signal degradation arises from mismatching of electrical characteristic impedances at cable terminations and from signal attenuation due to cable length. Impedances must be matched so that, at high frequencies, electromagnetic reflections cannot arise at the different impedance interfaces. Furthermore the cables must be as short as possible to reduce signal attenuation.

Signal degradation caused by shock and vibration have been the subject of reports by Perls (1952) and Linde and Schmidt (1966). Discussions can also be found in Grady (1969) and Mitchell and Nellis (1981).

5.2.2 Recording oscilloscopes

Where nanosecond resolution is required, such as in the study of shock induced conduction, oscilloscopes will be required with an analogue bandwidth greater than 375 MHz. There are many analogue oscilloscopes currently available on the market that meet this requirement. Recently the time response of digital sampling instrumentation has improved dramatically. A review has been made on the current status and future trends in digital sampling instrumentation (Parisi, 1985). Attention should also be drawn to digital oscilloscopes using superconductivity (Weber, 1987; Browne, 1987). This development means that the gauge response now limits the overall response time of the instrumentation.

6. CONCLUSION

The use of manganin gauges for the measurement of dynamic stresses in the range of 1 to 15 GPa with nanosecond resolution is possible using the 50 ohm gauge with 5 μm thickness. Detonation pressures in the range greater than 9 GPa can also be measured but time resolution is sacrificed because the gauge, bonding agent and insulation thickness must be thicker in order to survive longer in this environment. The installation of the gauges requires air evacuated epoxy. For preliminary investigations static loading tests are recommended. The following equipment are required :

(a) The 50 ohm manganin gauges.

(b) A hydrostatic press with an anvil enabling loads in 1-2 GPa range.

(c) A multimeter to measure the resistance change in the gauge.

For measurements in shock-loaded inert solids, e.g. involving spallation studies, the following equipment are required:

(a) The 50 ohm gauges with a constant voltage pulsed power supply.

(b) Electrical pins are required to trigger the power supply. In applications involving flyer plate impacts, pins can also be used for the measurement of the flyer plate velocity and tilt. Counters will also be required. (Flyer plate velocity and tilt can also be measured by either streak photography or VISAR).

(c) Digital oscilloscopes are needed where the data can be transferred directly to the computer for nonlinear corrections.

(d) Software is needed for the data corrections outlined in section 1 1.

(e) An understanding of shock wave physics to correlate the records with the material shock response.

Results can be compared with those in the published literature (Morris, 1982).

If the gauges are to be calibrated, the generation of plane shock waves will be required. This will present the greatest difficulty. A possible method is to use exploding foil plane shock wave generators.

To study shock-induced conduction with nanosecond signal rise time, the polymer PVF_2 gauge may need to be used. It can be made extremely thin (9 μm) and does not need as many insulation layers as the manganin gauge. Furthermore, high speed recording equipment will be required, preferably high speed digital oscilloscopes with sample rates fast enough to measure signals having a 1 ns rise time (sample rates of the order of 200 picoseconds). All electrical impedances will need to be matched. If pins are to be used, fast acting shorting pins will be required.

Detonation pressure measurements require the low impedance gauge which requires a constant current pulsed power supply. However the gauge insulation is very thick and perturbs material flow. If multiple gauges are to be inserted in the material, the Electromagnetic Velocity Gauge (EMV) should be considered (Figures 38, 39). This measures particle velocity but stress can be derived (Seaman 1974). Further investigations will be required.

Stress measurements which are not uniaxial, such as divergent shock wave measurements, require compensation for those strains not in the required direction (Larson and Stout 1987).

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TABLE 1

Manganin alloy properties

Resistivity ($\mu\Omega$ cm)	48 31-36	Steinberg and Banner (1979), p. 235. Chen, Gupta and Miles (1984), p. 3986. Gupta and Gupta (1987), p. 2603.
Mass density (no strain)	8.46 g/cm3	Partom, Yaziv and Rosenberg (1981), p. 4614, based on the results from Barsis, Williams and Skoog (1970).
Bulk sound velocity (no strain), c_0.	3.70 mm/μs	Partom, Yaziv and Rosenberg (1981), p. 4614, based on the results from Barsis, Williams and Skoog (1970).
Slope of shock velocity/ particle velocity, s.	2.28	Partom, Yaziv and Rosenberg (1981), p. 4614, based on the results from Barsis, Williams and Skoog (1970).
Dynamic yield stress, σ_{yield}.	0.75 GPa	For Micro-measurement gauges, Rosenberg and Brar (1988), p. 350.

TABLE 2

Manganin gauge shock loading response- major works

REFERENCE	COMMENT
Barsis, Williams and Skoog (1970).	Study of piezoresistance coefficient of manganin and the development of a model to account for different loading conditions, (1D, 2D and hydrostatic models). Always referenced in subsequent models.
Keough and Wong (1970).	Study of piezoresistance coefficient of manganin in different insulation materials. Concludes that the manganin transducer must be used as a foil with high apect ratio (as high as 100:1) in order to measure principal stresses.
Lee (1973); Gupta (1983a).	Study of nonlinearity of the piezoresistance coefficient of manganin.
Kanel, Vakhitova and Dremin (1978); Steinberg and Banner (1979) Vantine et al (1980b) Yaziv, Rosenberg and Partom (1981).	Study of manganin gauge hysteresis and presentation of methods for correction through empirical expressions derived from calibration experiments.
Gupta et ak (1980); Rosenberg, Yaziv and Partom (1980); Rosenberg, Partom and Yaziv (1981); Rosenberg and Brar (1988).	Development of the "in situ" transverse placement of the gauge.
Partom, Yaziv and Rosenberg (1981).	Elastoplastic model relating polycrystalline behaviour tc single-crystal randomly orientated grains (grains model).
Gupta (1983b); Gupta and Gupta (1987a); Gupta and Gupta (1987b).	Electromechanical model for piezoresistance and and an elastic-plastic inclusion analysis (inclusion analysis model).
Rosenberg, Partom and Keren (1983); Chen, Gupta and Miles (1984).	Correlation of quasistatic measurements to dynamic measurement and manganin gauge characterisation.

TABLE 3

Variations in the electrical element of the manganin gauge transducer

TYPE	RESISTANCE (ohms)	APPLICATIONS	REFERENCE
Wire	0.50	Detonation pressure measurements.	Burrows, Chivers, Gyton, Lambourn and and Wallace (1976).
Foil	0.06-4.0	Shock compression and unloading in inert solid materials.	Kanel, Vakhitova and Dremin (1978).
Foil	0.11	Shock compression and unloading in inert solid materials.	Gupta and Gupta (1987a).
Foil	0.50	Shock compression in inert materials.	Yasumoto, Kondo and Sawaoka (1980).
Foil	48-50	Shock compression and unloading in inert materials.	Rosenberg, Yaziv and Partom (1980). Micro-Measurements (1988).
Foil	0.020-0.060	Detonation pressure measurements.	Vantine et al (1980a) Dynasen Inc. (1982).
"T"	-	Sweeping shock pressure loads.	Duggin and Butler (1970) Micro-Measurements (1988), gauge 580SF.
Strain Compensated	-	Conditions where plastic deformation occurs. Gauge consists of manganin and constantan.	Trimble (1979). Titov, Karakhanov and Bordzilovsky (1985).
Interlaced		Conditions where plastic deformation occurs.	Dynasen Inc. (1982), gauge Mn-Cn4-50-EK. Larson and Stout (1987).

TABLE 4

Bonding agents with known Hugoniots response curves

TYPE	PROPERTIES AND MANUFACTURER	REFERENCE
Hysol 2038 resin, Hysol H2-3404 hardener	Cures in 24 h at room temperature The Dexter Corporation	Barker and Hollenbach (1970), p. 4209.
Hysol 0151 Epoxi-Patch	Clear, approx. sp. gr. part A=1.6, part B=1.5, cures in 24 h at R.T., The Dexter Corporation	Ovid et al (1978), p. 87.
C-7/A	Clear, mixed system sp. gr.=1.189, cures in 7 days at R.T., Armstrong Products, Inc., Warsaw, Ind.	Keough et al (1970), Table I. Lee (1973), Table I.
Epon 828 with metaphenyl-enediamine(12.6%) hardener.	Mixed system sp. gr. = 1.194, cures in 56 h cycle, Shell Oil Company	Munson et al (1972), p. 964, Table I.
Epon 828 with Z (16.6%) hardener	Mixed system sp. gr. = 1.20, cures in 24 h cycle, Shell Oil Company	Munson et al (1972), p. 964, Table I.
Epon 828 with D (13%) hardener	Mixed system sp. gr. = 1.162, cures in 24 h/ 74 C, Shell Oil Company	Munson et al (1972), p 964, Table I.
Epon 828 with diethanclamine as hardener.	Mixed system sp. gr. = 1.198 Shell Oil Company	Kinslow (1970), p. 557.
Epon 828 with versamide (?) hardener	Resin sp. gr. = 1.125, Mixing ratio (70/30) Shell Oil Company. (Possibly versamide 125)	Rosenberg (1981), p. 4000.

TABLE 5

Insulators with known Hugoniots response curves

TYPE (Trade name)	density g/cm^3	$u_s = c_o + sup\ s$ c_o km/s		RANGE (km/s)	REFERENCE
Polyimide (Kapton)	1.414	0.93	1.64	?	Marsh (1980).
Polyethylene terephtalate (Mylar)	2	0.27	1.50	?	Marsh (1980).
Polytetra-fluoroethylene (Teflon)	2.151	1.68	1.79	0.6-2.8	Graham (1979), p.3051, Table III.
Mica	2.6-3.2	?	?	?	Weast (1988) Table F-1.

TABLE 6

Sources of manganin alloy

DESCRIPTION	SOURCE	REFERENCE
Wire 0.127 mm diameter	Atomic Weapons Research Establishment	Burrows et al (1976), p. 625.
Wire approx. 0.254 mm diameter	Wilbur B. Driver Co.	Steinberg and Banner (1979), p. 235.
Wire various sizes	Driver-Harris Co. Harrison, New Jersey	Keough (1968), p. 23. Barsis et al (1970), p. 5155. Keough et al (1970), p. 3509. Lee (1973), p. 4017. De Carli et al (1976), p. 17.
Foil approx. 0.030 mm thickness cold rolled	Hamilton Tech Lancaster, PA	Chen et al (1984), p 3986. Gupta and Gupta (1985b), p. 509. Gupta and Gupta (1987a), p. 2603.
Foil 0.025 mm thick annealed shunt grade	Hamilton Tech Lancaster, PA	Erickson et al (1979), 21-1.

TABLE 7

References that include power supply details and recording instrumentation

REFERENCE	COMMENT
Keough (1968) pp. 41-59, 75-84. Summary in Murri, Curran, Peterson and Crewdson, (1974), pp. 59-73.	Very detailed account. Includes details on instrumentation recording techniques.
Williams (1968), pp 15-17.	Brief account of constant current and constant voltage power supplies. Also provides a comprehensive account of manganin gauge instrumentation.
Grady (1969).	Discussion of constant current power supply. Includes circuit diagram and discusses signal transmission problems.
Rice (1970).	The most comprehensive discussion on the wheatstone bridge configuration for the 50 ohm gauge.
Fowles and Williams (1970), pp. 994-5.	Brief account of power supply with a circuit diagram. However includes details of other instrumentation such as a gas gun, tilt and velocity pins.
Williams (1971).	The most comprehensive account of a power supply. Includes assembly drawings. This appears to be the most sophisticated ever developed.
Oved, Luttwak and Rosenberg (1978), p. 87-88.	Brief account of constant voltage power supply. The most simplest configuration used in the literature and the most practical.
Vantine et al (1980a), p. 117.	Brief account of constant current power supply for low impedance gauge. Includes a circuit diagram. A very sophisticated and practical design.
Gupta and Gupta (1985a), pp. 2465-2466.	Although ytterbium gauges are discussed, the recording instrumentation is the same. Includes a circuit diagram for recording the signal.
Jacques, Belanger and Matte (1985), pp. 28-34.	Derivation of bridge equations which considers the amplifier impedance.

TABLE 8

Some important reviews on shock waves in condensed matter

REFERENCE	COMMENT
Rice, McQueen and Walsh (1958)	First comprehensive review. Develops basic conservation laws, discusses experimental methods and presents equation of states of metals (dated).
Duvall and Fowles (1963)	Excellent introduction, develops conservation laws for experimental techniques. Extensive coverage of experimental techniques (dated).
Al'tshuler (1965)	An extensive discussion on all aspects of shock waves in solid materials.
Skidmore (1965)	Excellent introduction to shock waves in inert solids.
Zel'dovich and Raizer (1966)	Excellent coverage of all aspects of shock waves and full of powerful insights.
Kinslow (1970)	Chapter VII is a standard reference on equation of states of solids.
Chou (1973)	Compilation of articles by various authors. Covers theoretical and experimental aspects.
Schuler and Nunziato (1973)	Review of the theories of shock and acceleration wave propagation in materials with memory and correlation with experimental results (advanced treatment).
Murri, Curran, Peterson and Crewdson (1974)	Comprehensive, covering theory and experimental techniques.
Duvall and Graham (1977)	The most comprehensive review of shock-loaded inert solids undergoing phase transitions.
Graham and Asay (1978)	The most comprehensive review on experimental techniques.
Davidson and Graham (1979)	The most comprehensive review on shock waves in inert solids.
Yadav (1979)	Introduction to experimental techniques.

TABLE 8
(continued)

REFERENCE	COMMENT
Zukas et al (1982)	Compilation of articles by several authors. Excellent introduction on impact dynamics.
Mogilevsky (1983)	Discusses relationship between deformation and shock loading.
Clifton (1983)	Review on the dynamic plastic response of crystalline materials.
Malvern (1984)	A selective review on experimental and theoretical approaches to characterisation of material behaviour at high rates of deformation. A valuable comparative discussion on the different approaches used.

TABLE 9

Reported time resolution of the manganin gauge, bonding agent and insulation assembly

CONFIGURATION	GAUGE TYPE & THICKNESS (μm)	TIME RESOLUTION (ns)	AUTHOR
Back surface; PMMA backing.	grid 5	of the order 1	Rosenberg and Bless (1986), p. 1384.
Back surface; Epoxy backing.	grid 5	of the order of a few ns	Rosenberg (1986), p. 3107.
"In situ"	grid 5	of the order of a few ns	Using the formula in Williams (1968), p. 12
"In situ"	grid approx. 20	10	Fowles et al (1970), p. 994.
"In situ"; Unreacted Explosive.	strip 25	approx. 10	Vantine et al (1980a), p. 120.
"In situ"; Reacted Explosive.	strip 25	40	Vantine et al (1980a), p. 120.
"In situ"; plastic like materials & composites.	strip 25	50	Dynasen Inc. (1982)
"In situ"	-	30-50	Fowles (1972), p. 470.
"In situ"; insulators.	-	10-20	R. G. McQueen in Morris (1982), p. 9.

APPENDIX 1

A note on the terminology used in the literature on shock waves in condensed matter

Throughout the literature on shock waves in condensed matter one encounters the use of many terms which have been borrowed from different branches of physical science. This isn't surprising because to explain the changes observed in the properties of the material many aspects of the behaviour of the material have to be considered involving the use of thermodynamics, kinematics, solid and fluid mechanics, wave theory, acoustics etc. The use of these borrowed terms leads to vagueness and inconsistency. For this reason it is necessary to define certain terms used in the body of this report and to point out their origin and context.

"Material response" refers to the behaviour of the material due to its inherent mechanical properties. This is in contrast to its "structural response" where the shape of the material is important. Because of the enormous internal stresses generated by shock waves in condensed matter, interest is predominantly confined to the material response.

When one considers the dynamic point of view a difference is drawn between the rate and manner a load is applied to a material. The rate at which the load is applied leads to a classification in terms of the rate of deformation of the material, viz. the strain rate $\dot{\epsilon}$. If high strain rates are involved, of the order of 1-100 s, the load is called "dynamic". Here wave propagation phenomena become important due to system inertia effects. Furthermore the material response becomes dependent on $\dot{\epsilon}$, i.e. there is rate dependence on microstructural processes. If much lower strain rates are involved then the load is called "static" and if they involve strain rates approaching those due to dynamic loads they are called "quasistatic loads". In work involving shock wave measurements, dynamic loads are produced exclusively by shock waves from explosives or gas gun impacts. Experiments are expensive and the loads cannot be applied continuously. On the other hand static loads are produced in pressure cells and are inexpensive, easier to achieve and loads can be generated continuously in a single experiment. However they are of limited use in shock wave measurements because of the difference in material response. Of great importance are the quasistatic loads which are also generated in pressure cells but can be correlated to the dynamic material response.

A further classification of dynamic loads involves the manner in which a load is applied. This scheme considers the shock geometry and assumes that the shock is a mathematical discontinuity where the material undergoes abrupt changes in its properties behind the shock. In this classification dynamic loads are said to be either "planar" or "nonplanar". Planar loads are infinite in extent and involve shocks with a plane profile. If the direction is normal to the shock front

then it is a "normal shock". If the direction is at an angle other than normal then it is an "oblique shock". Nonplanar loads usually involve "divergent shocks" which are of spherical profile and expand as they propagate in the material.

Another point of view which is commonly used in the study of shock waves is the kinematic point of view where a choice is made on the frame of reference. If the laboratory is used, the observation is confined to a fixed point in space and in the changes in the properties of the material at this point. This is referred to as the "Eulerian viewpoint". Alternatively one can follow a point mass throughout the experiment and observe its changes. This is referred to as the "Lagrangian viewpoint". The Eulerian and Lagrangian viewpoints have deeper physical significance in their thermodynamic equivalents, the system volume and control volume approaches, respectively. They also appear in fluid mechanics in the formulation of the conservation equations in terms of the space and time derivitives or the material derivitive, respectively. In this case one also speaks of the flow of the fluid as being steady or unsteady, terms which also appear in the literature. In the context of shock waves in condensed matter, the flow is said to be steady if the shock wave profile is the same throughout the time of the experiment and unsteady if it changes. The commonly used Rankine-Hugoniot equations use the Eulerian viewpoint of the conservation equations for steady flow. Note however that embedded gauges sense in the Lagrangian frame of reference.

Some further terms that are commonly used in the literature have precise mathematical definitions, refer to Tables A-1(a) and A-1(b).

TABLES A-1(a) and A-1(b)

Mathematical definitions of some commonly used terms in the literature on shock waves in condensed matter.

Table A-1 Wave Types

Term	Mathematical Definition
Shock wave	Strain, particle velocity and temperature are discontinuous. Stress and internal energy are generally discontinuous (Schuler and Nunziato p. 1240).
Acceleration wave	Strain, particle velocity and temperature are continuous. Their derivitives with respect to distance are discontinuous. (Schuler and Nunziato p. 1240).

Table A-2 Type of shock wave

Term	Mathematical Definition*	Example	Reference
Uniaxial stress or plane stress or one dimensional (1D) stress.	$\sigma_x = \sigma_x(x)$, $\epsilon_y = \epsilon_z$ $\sigma_z = \sigma_y = 0$ $\tau_{xy} = \tau_{yz} = \tau_{zx} = 0$	Tension and compression waves in a bar.	Zukas et al 1982, pp. 96-131. Chou and Hopkins 1972, pp. 70-71.
Uniaxial strain.	$\epsilon_x = \epsilon_x(x)$, $\sigma_y = \sigma_z$ $\epsilon_y = \epsilon_z = 0$ $\epsilon_{xy} = \epsilon_{yz} = \epsilon_{zx} = 0$	Plate impact tests (Diameter of plate > 3 times its thickness to eliminate radial reflections).	Zukas et al 1982, pp. 131-143. Chou and Hopkins 1972, pp. 67-70.
Hydrodynamic compression.	$\sigma_x >> \sigma_{yield}$ and $\tau_{xy} = \tau_{yz} = \tau_{zx} = 0$	Dynamic loads in metals > 100 GPa.	
Hydrostatic compression.	$p = -\sigma_x = -\sigma_y = -\sigma_z$ $\epsilon_x = \epsilon_y = \epsilon_z$	Isotropic fluid under static loading.	

* Note: σ denotes compressive stress,
τ shear stress and
ϵ strain.

The direction of the shock wave is in the x direction. Note also that σ_{yield} denotes the compressive yield strength of the material.

APPENDIX 2

Calibration through shock impedance matching

Shock impedance matching is a method of relating shock wave propagation in materials to the materials' thermodynamic properties. Use is made of the conservation laws (mass, momentum and energy) and the shock Hugoniot which is effectively an equation of state of the material.

The shock Hugoniot is derived experimentally (Rice, McQueen and Walsh 1958). It is a relationship between the shock wave velocity u_s, and particle velocity u_p, in the form of :

$$u_s = c_o + su_p$$

where c_o and s are material constants. c_o is referred to as the material bulk sound velocity and is normally the speed of sound in the material under the measurement conditions.

Calibration is achieved in the following manner:

(a) A flyer plate accelerated to hypervelocity impacts onto a target. The gauge is embedded in the target, i.e. in the "in situ" configuration.

(b) A measurement is made of the particle velocity of the target material. The particle velocity is commonly determined by the free surface velocity method (Duvall and Fowles, 1963, pp. 233-243) which involves the measurement of the back surface shock velocity.

(c) The stress in the target material is evaluated graphically from the Hugoniot curve which is a plot of stress in the material versus particle velocity. The method involves the reflection of this curve (Duvall and Fowles 1963, pp. 219-223).

(d) The voltage output from the gauge can then be correlated to the stress level determined above.

Calibration experiments can be:

(a) symmetric, where the flyer plate and target consist of the same material (Rosenberg, Yaziv and Partom, 1980);

(b) nonsymmetric, where different materials are used for the flyer plate and target;

(c) release, where a second target is bonded to the rear of the first material and reflections from the material interfaces propragate back to the gauge (Yaziv, Rosenberg and Partom, 1981).

The overall accuracy of this technique is believed to be within 1-3 % (Vantine et al, 1980b, p. 1960).

APPENDIX 3

Piezoresistance gauge constants

In the study of piezoresistance gauges it is useful to define two constants which relate to changes in resistance, length and stress. Let

σ_x = the stress perpendicular to the plane of the gauge,

δR = the accompanying change in resistance of the gauge,

δl = the accompanying change in length in the gauge,

R_g = the initial resistance of the gauge,

l_o = the initial length of the gauge,

then the following proportionality constants can be defined:

1. Piezoresistance coefficient:

$$K = (\delta R/R_g) / \sigma_x \qquad (1)$$

This form is useful for the calibration of piezoresistance gauges. For manganin the linearity between the change in resistance and stress breaks down at 1.5 GPa where a third or fourth degree polynomial in change in resistance is required.

2. Gauge factor (or strain coefficient):

$$GF = (\delta R/R_g) / (\delta l / l_o) \qquad (2)$$

This expression has been used in studying the stress conditions on the gauge. As in the case of the piezoresistance coefficient, this linearity breaks down. For example, it has been shown that under uniaxial stress conditions the gauge factor is between 0.67 (Trimble, 1979, p. 12) and 0.69 (Partom, Rosenberg and Keren, 1984, pp. 552-553). At large strains the gauge factor approaches 2 (Trimble, 1979, p. 28).

For a discussion of piezoresistance in terms of crystal structure refer to Mason (1966) and Smith (1958).

SYMBOLS

c_o	Bulk sou id velocity of the material.
GF	Gauge factor or strain coefficient of the piezoresistance gauge.
K	Piezoresistance coefficient.
l_o	Initial length of the piezoresistance gauge prior to deformation.
R_g	Initial resistance of the piezoresistance gauge prior to deformation.
s	Slope of the shock Hugoniot of a given material.
sp. gr.	Specific gravity.
u_s	Velocity of the shock wave in the material.
u_p	Particle velocity.
V_o	Power supply voltage to the piezoresistance gauge.
δl	Change in length in the piezoresistance gauge due to the induced stress.
δR	Change in resistance of the piezoresistance gauge due to the induced stress.
δV	Change in voltage in the piezoresistance gauge due to the induced stress.
ϵ_x	Strain component in the material due to the shock where the shock is assumed to travel in the x direction.
σ_x	Compressive stress component in the material due to the shock where the shock is assumed to travel in the x direction.
τxy	Shear stress component in the material due to the shock where the shock is assumed to travel in the x direction.

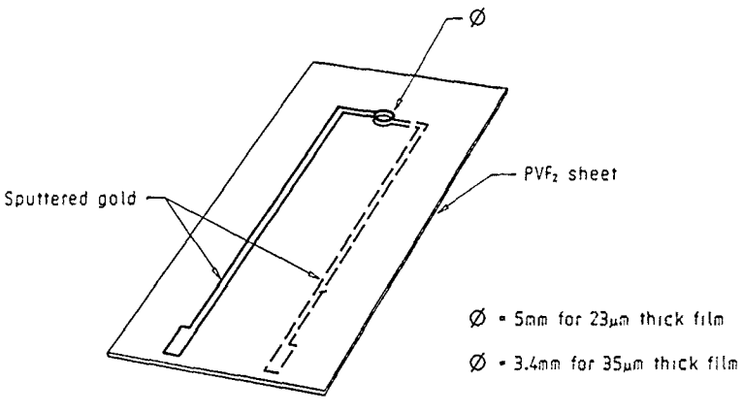


Figure 1 *Schematic of the Bauer ISL type polymer PVF_2 shock stress gauge. Refer to Reed (1987) for a discussion.*

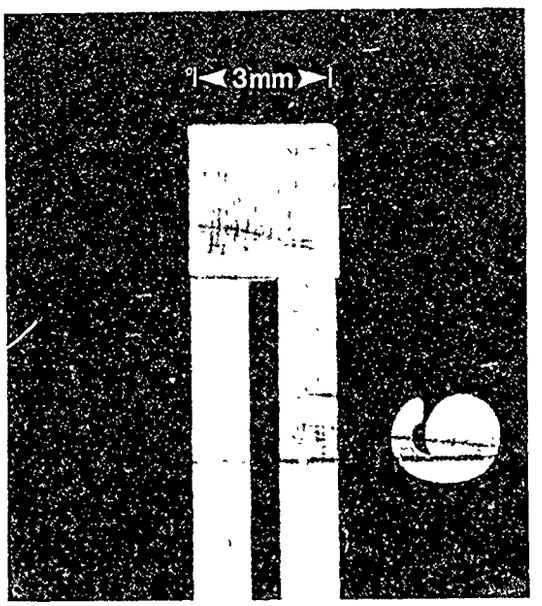


Figure 2 *Detail showing the Dynasen Inc. polymer PVF_2 shock stress gauge. Refer to Charest and Lynch (1987) for a discussion.*

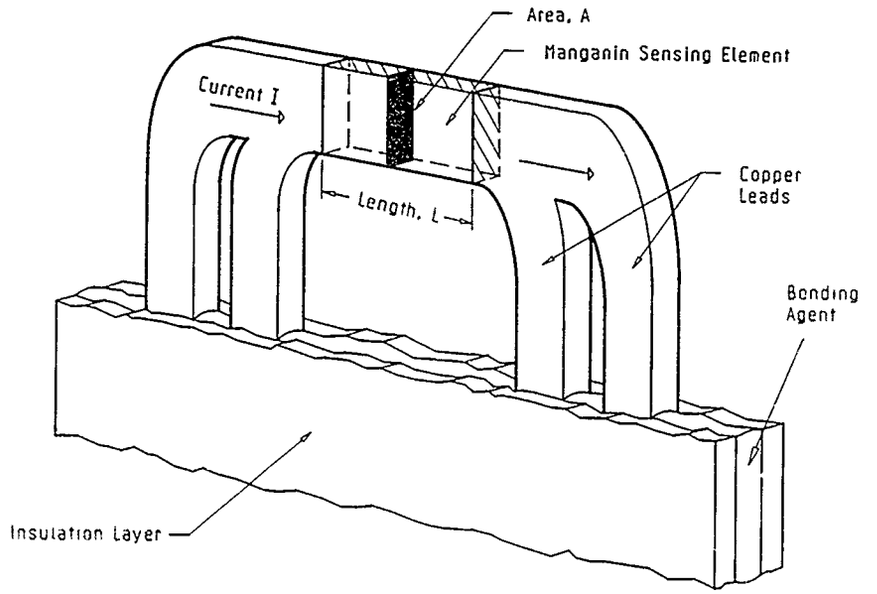


Figure 3 *Schematic of manganin gauge illustrating principle of operation. The type of gauge shown is the low impedance gauge. Measurements are conducted by measuring the resistance change across the sensing element.*

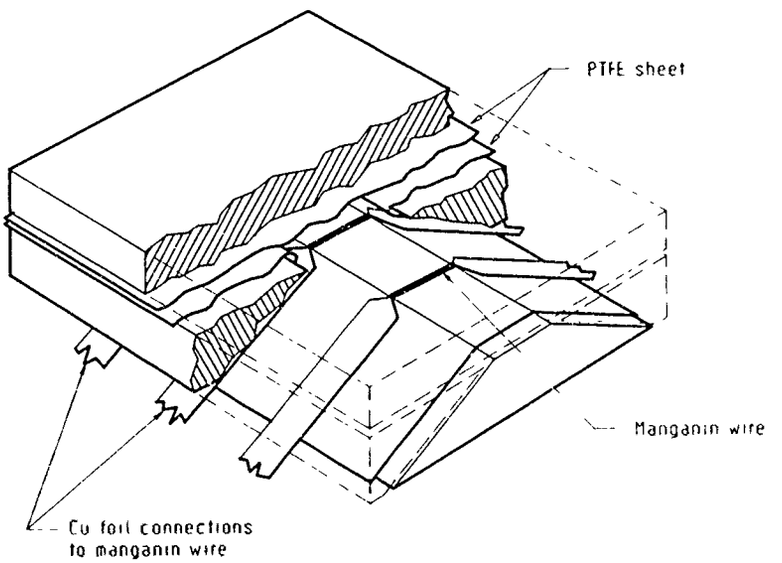


Figure 4 *Wire type manganin gauge for explosive measurements (adapted from Fuller and Price 1969, p 21). The gauge is insulated by sheets of PTFE which have been bonded using an epoxy (Araldite).*

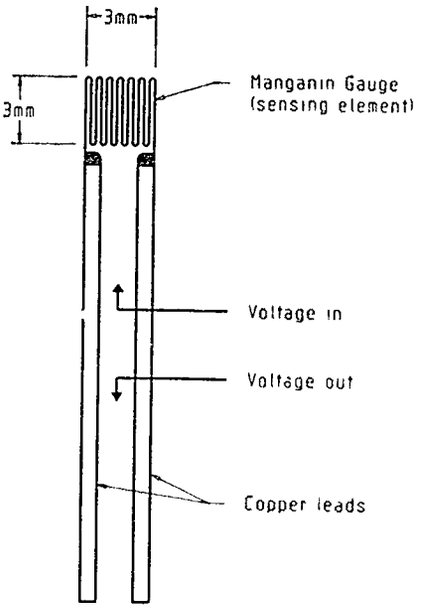


Figure 5 *Schematic of grid foil type manganin gauge (adapted from Wackerle, Johnson and Halleck 1975, p 21).*

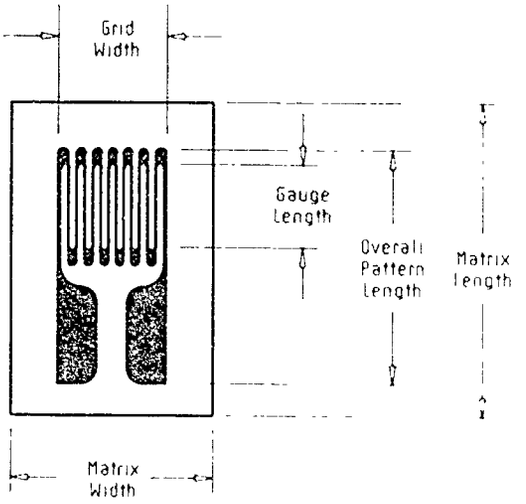


Figure 6 *Nomenclature used in piezoresistance foil gauges.*

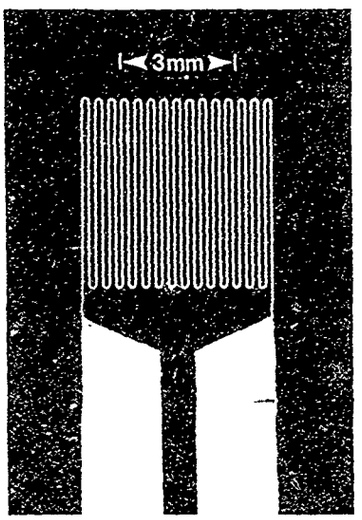


Figure 7 *Detail showing Dynasen Inc. grid foil type manganin gauge.*

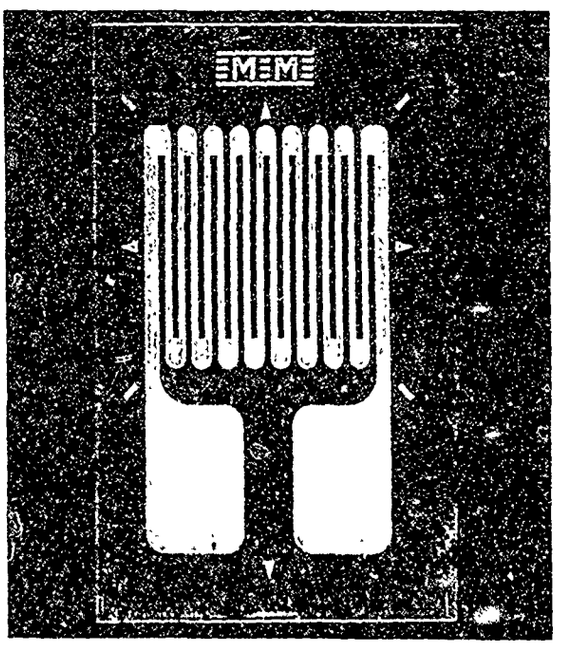


Figure 8 *Detail showing Micro-measurements' grid foil type manganin gauge VM-SS-125CH-048.*

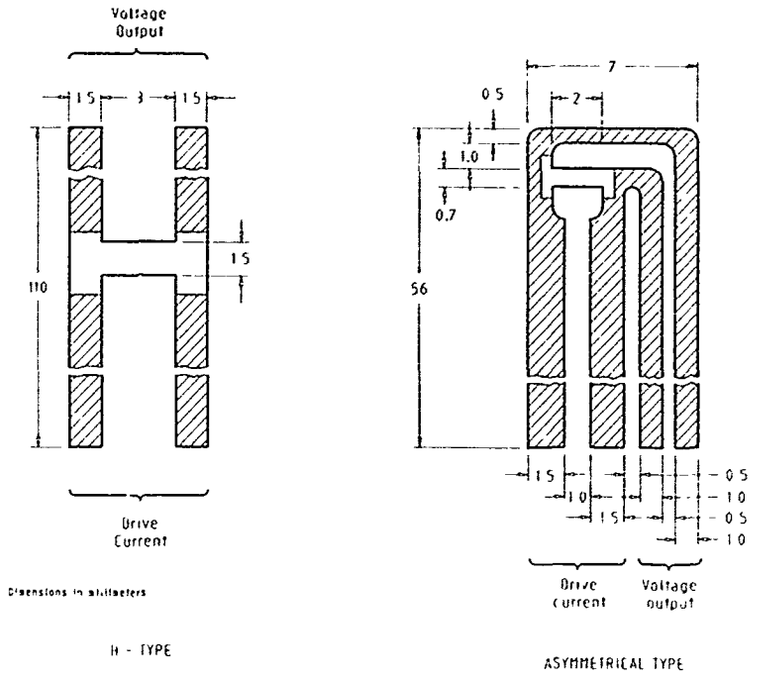


Figure 9 *Schematic of strip foil type manganin gauge (adapted from Vantine et al, 1980b, p. 1958). Double sided and single ended gauges are shown.*

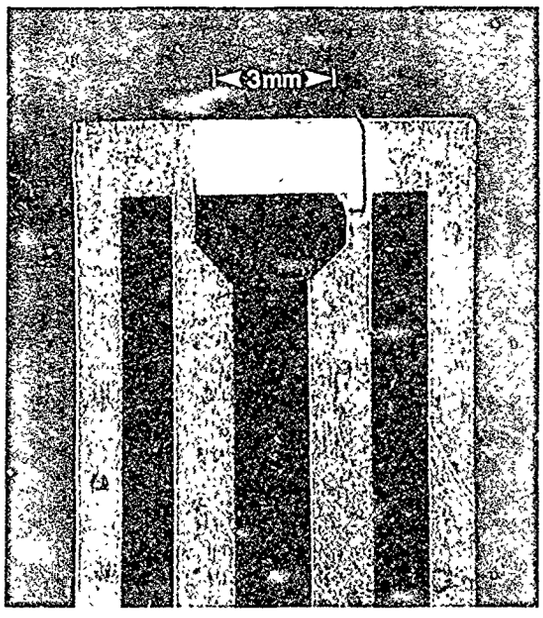


Figure 10 *Detail showing Dynasen Inc strip foil type manganin gauge Mn 10-0.050-FEP Type S (symmetrical).*

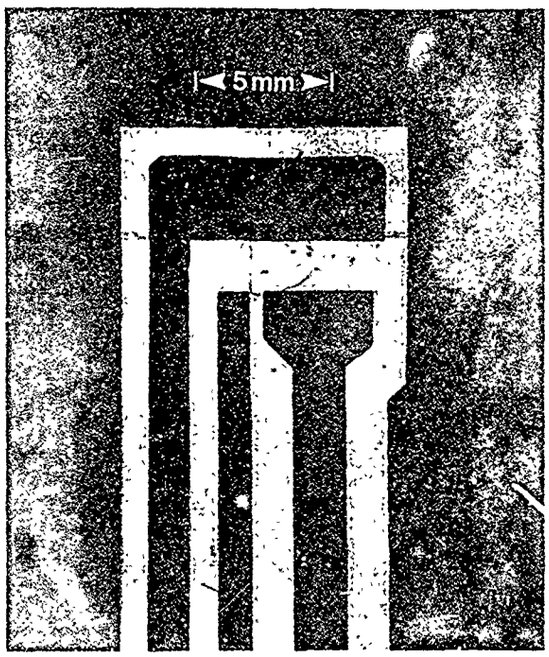
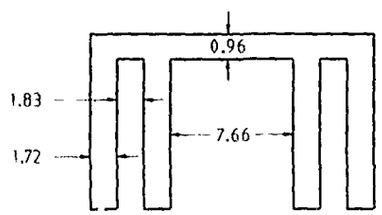


Figure 11 *Detail showing Dynasen Inc. strip foil type manganin gauge Mn 10-0.050-FEP Type AS (Asymmetrical).*



Dimensions in millimeters

Figure 12 *Strip type gauge used for the study of the response of manganin (Gupta and Gupta 1987a). The gauge consits entirely of manganin.*

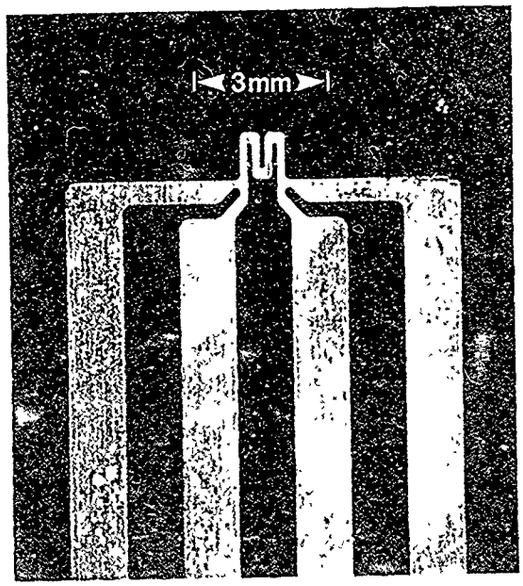


Figure 13 *Detail of foil type gauge from Micro-measurements.*

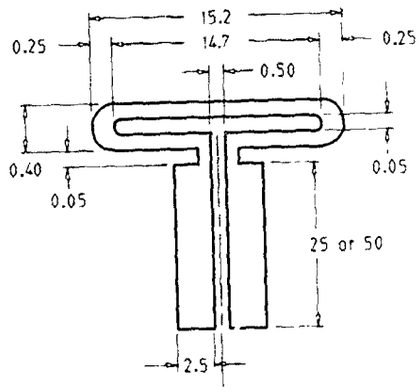


Figure 14 *Schematic of "T" type manganin gauge for measurements involving sweeping loads (Duggin and Butler 1970).*

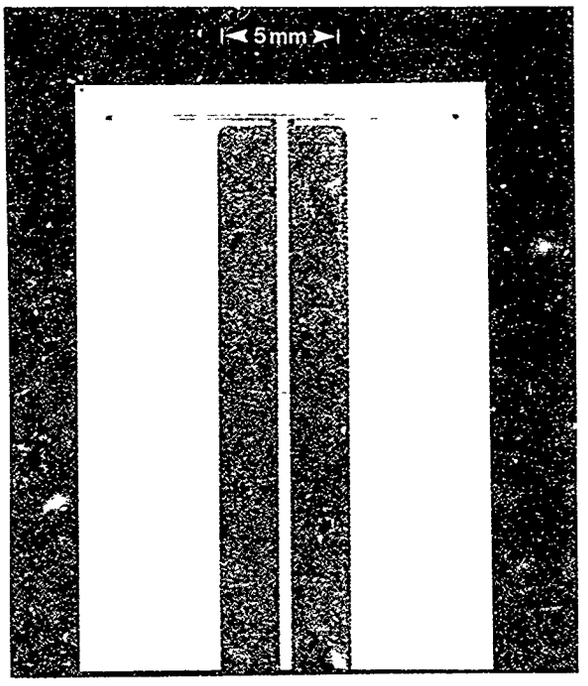


Figure 15 *Detail of a commercial "T" type manganin gauge, micro-measurements LM-SS-580SF-025.*

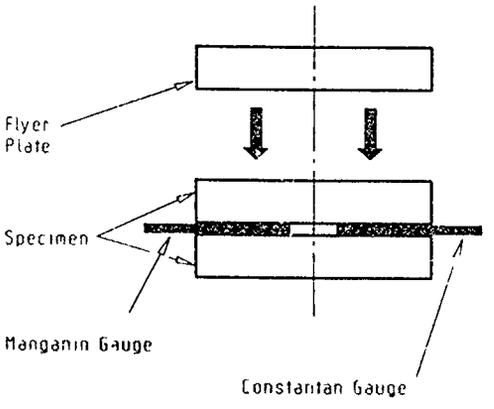


Figure 16 *Schematic of strain compensated gauge configuration for divergent shock measurements (Titov, Krakhanov and Bordzilovsky 1985).*

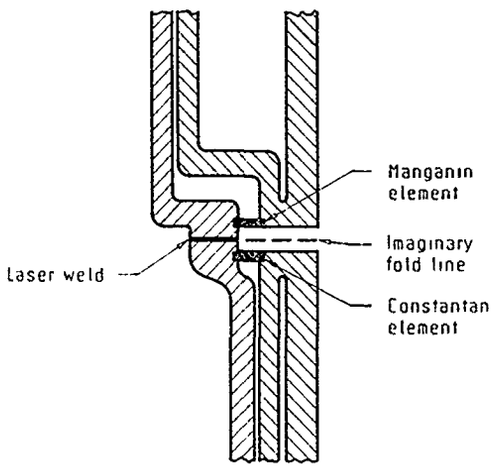


Figure 17 *Proposed construction of strain compensated manganin gauge (Erickson et al 1981b).*

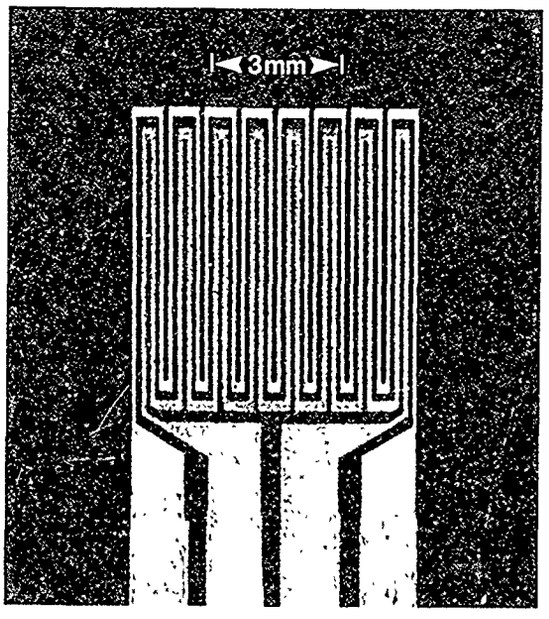


Figure 18 *Detail of Dynasen Inc. interlaced manganin/constantan gauge for divergent shock measurements.*

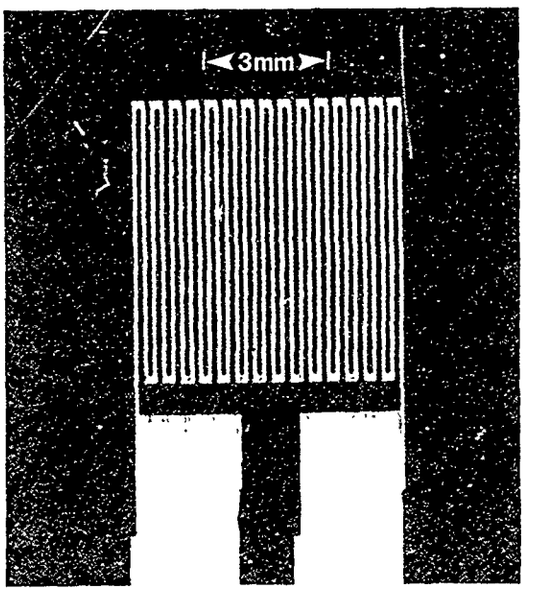


Figure 19 *Detail of Dynasen Inc. ytterbium gauge for low stress measurements (1-2 GPa). Refer to Gupta and Gupta (1985a) for a discussion.*

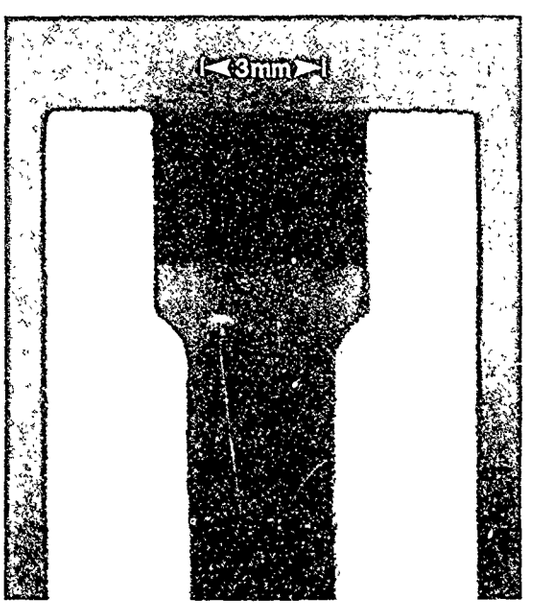


Figure 20 *Detail of Dynasen Inc. carbon gauge for low stress measurements (1-2 GPa). Refer to Horning and Isbell (1975) for a discussion.*

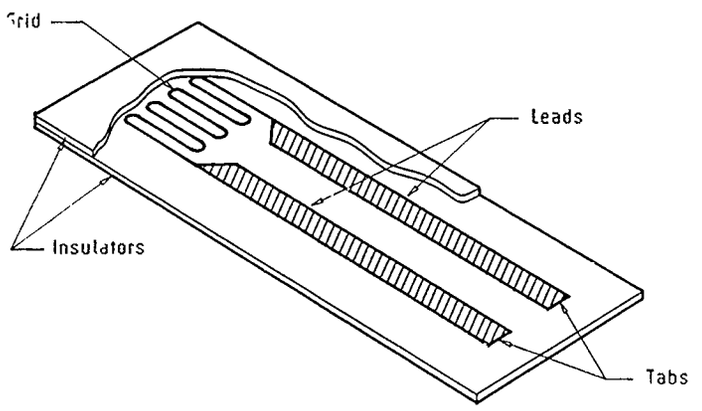


Figure 21 *Schematic illustrating manganin gauge with insulation and bonding agent.*

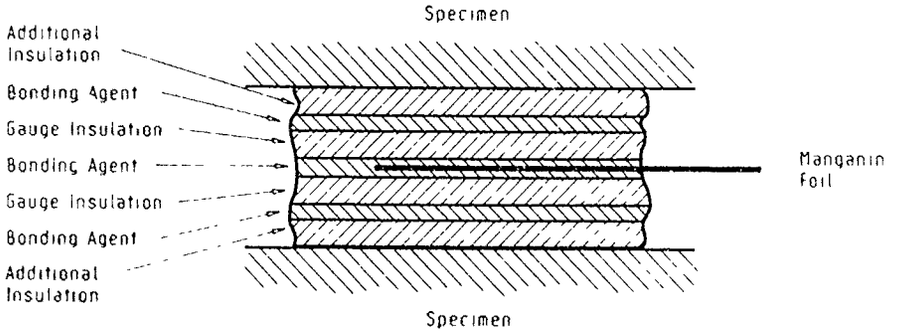
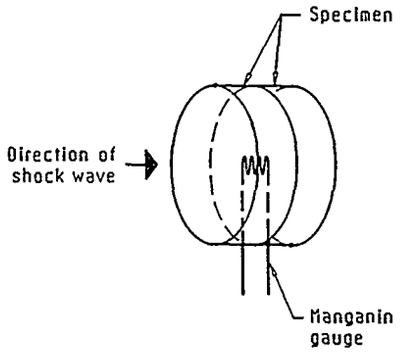


Figure 22 *Cross section showing manganin gauge insulation layers.*



IN SITU

Figure 23 *"In situ" placement of manganin gauge.*

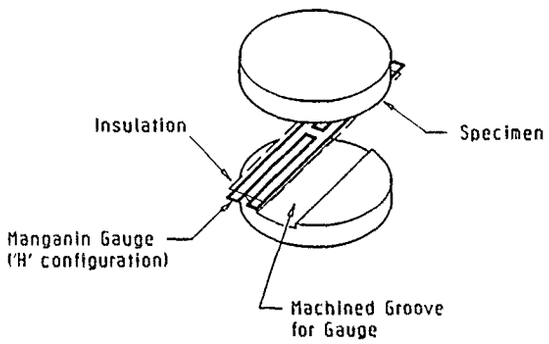


Figure 24 *Method of emplacement of manganin gauge to reduce impedance mismatching (adapted from Ginsberg, Anderson and Wackerle 1981).*

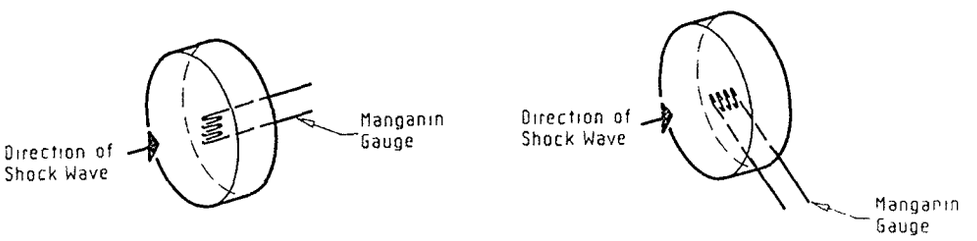


Figure 25 *Lateral or transverse "in situ" placement of manganin gauge (Rosenberg, Yaziv and Partom 1980, Rosenberg and Partom 1985).*

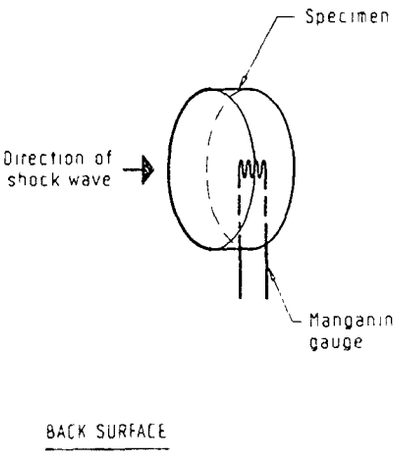


Figure 26 *Back surface placement of manganin gauge.*

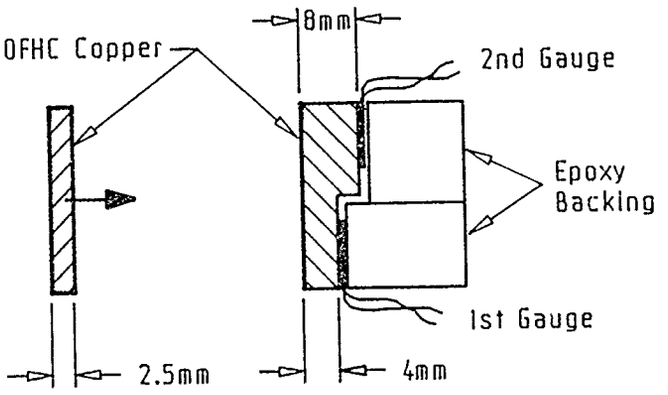


Figure 27 *Method of attachment of manganin gauge in the back surface configuration (Rosenberg 1986).*

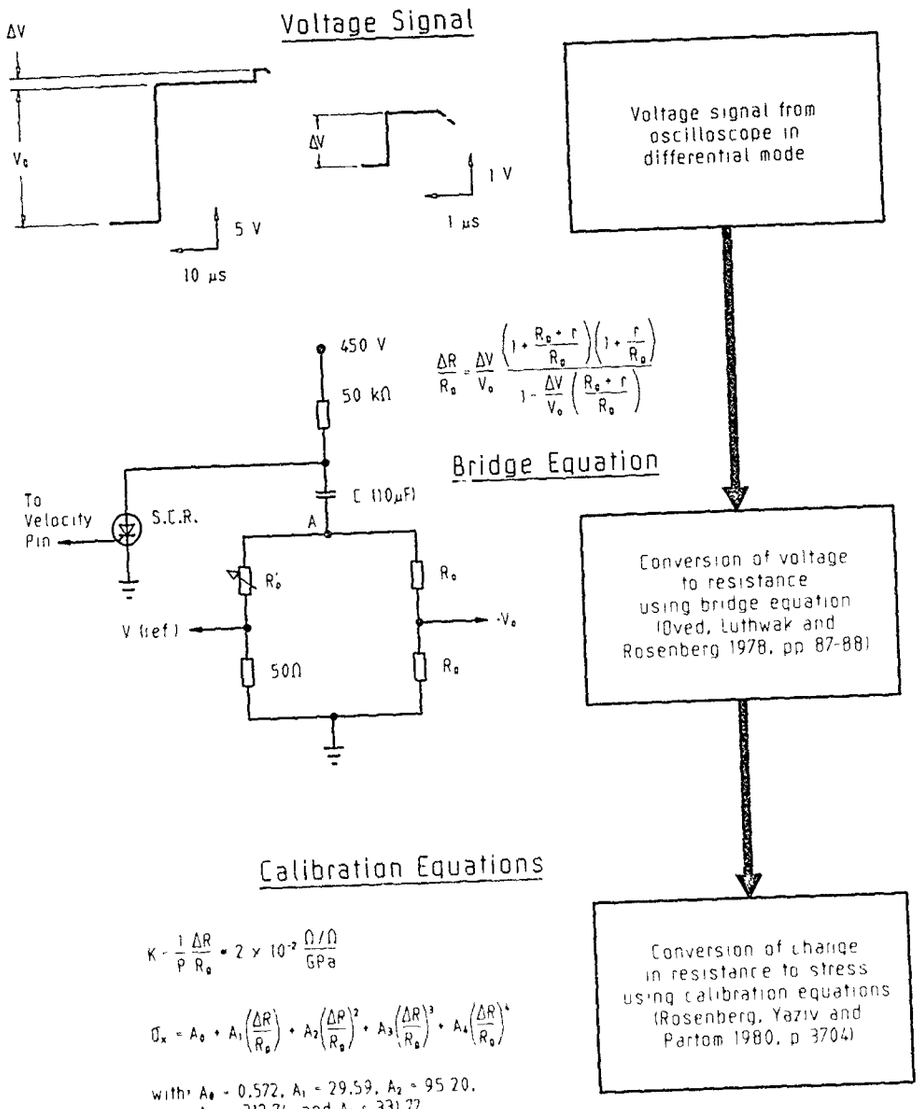


Figure 28 *Schematic illustrating corrections required for wheatstone bridge and manganin gauge nonlinearity corrections.*

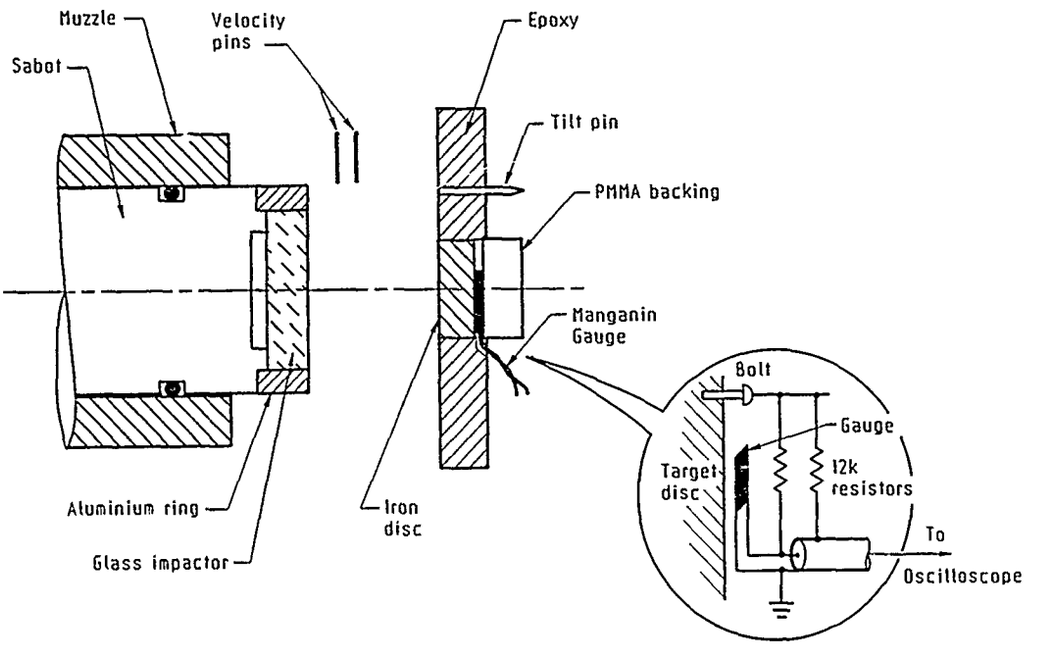
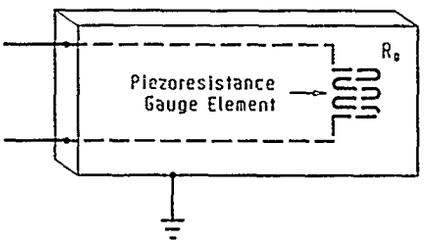


Figure 29 *Schematic showing electrical corrections required for noise created from two conductive materials in relative motion (Rosenberg, Erez and Partom 1983).*



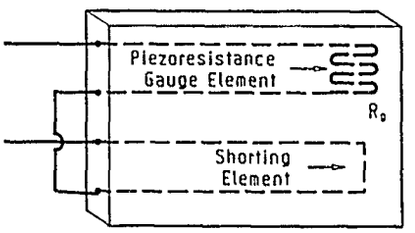


Figure 30 *Schematic showing electrical corrections required for noise created from inductive pick-up (Tokheim, 1986).*

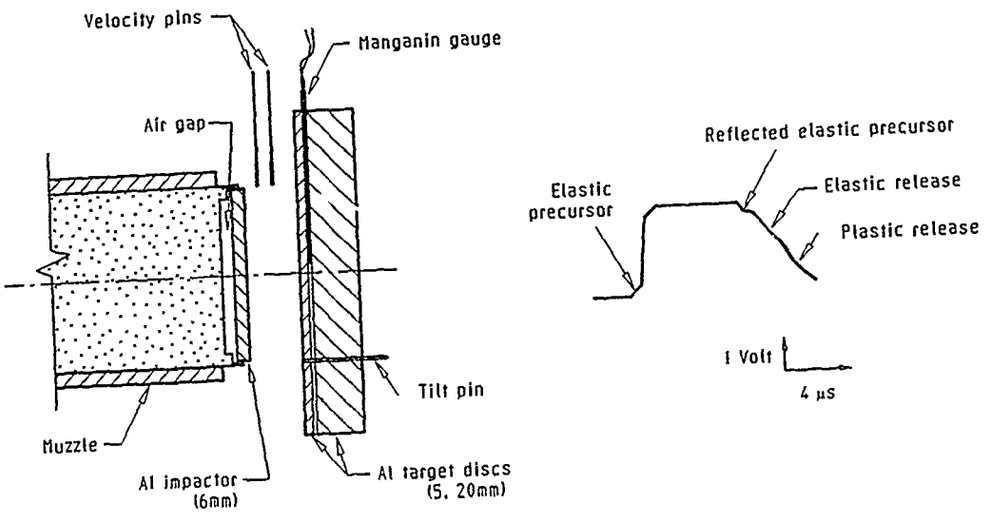


Figure 31 *Experimental set up and results illustrating stress profile in a ductile material (Yaziv, Rosenberg, and Partom 1982).*

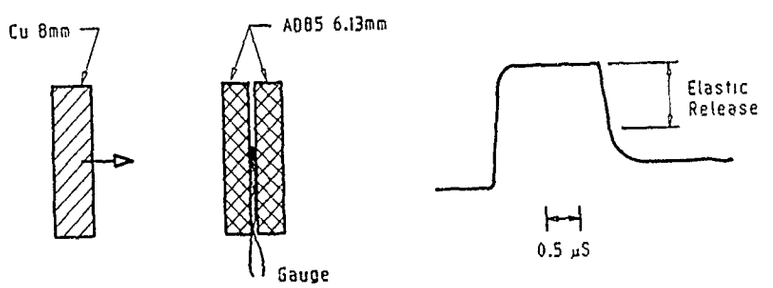


Figure 32 *Experimental set up and results illustrating stress profile in a brittle material (Rosenberg and Yeshurun 1985).*

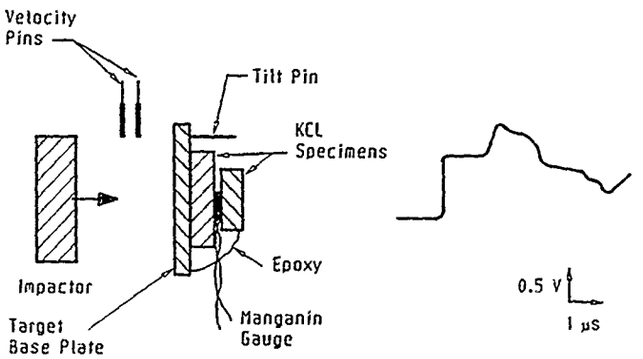


Figure 33 *Experimental set up and results illustrating stress profile in a material undergoing phase transformation (Rosenberg 1982).*

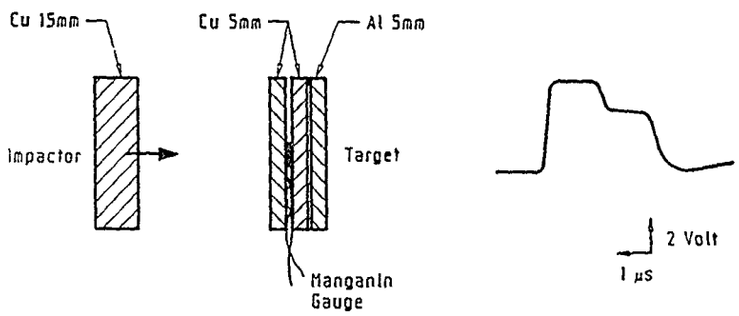


Figure 34 *Experimental set up and results illustrating stress profile pattern created from reflections at material interfaces (Rosenberg 1981).*

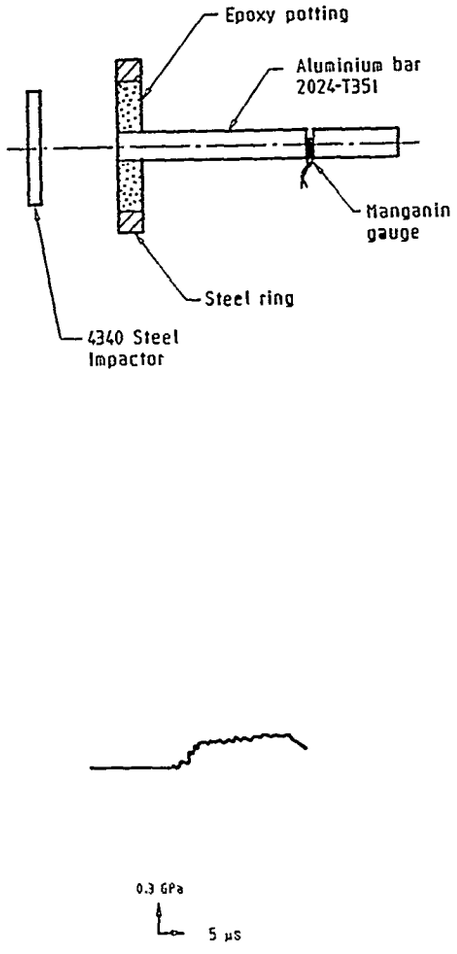


Figure 35 *Experimental set up and results illustrating stress profile in a rod (Rosenberg, Mayless and Partom 1984).*

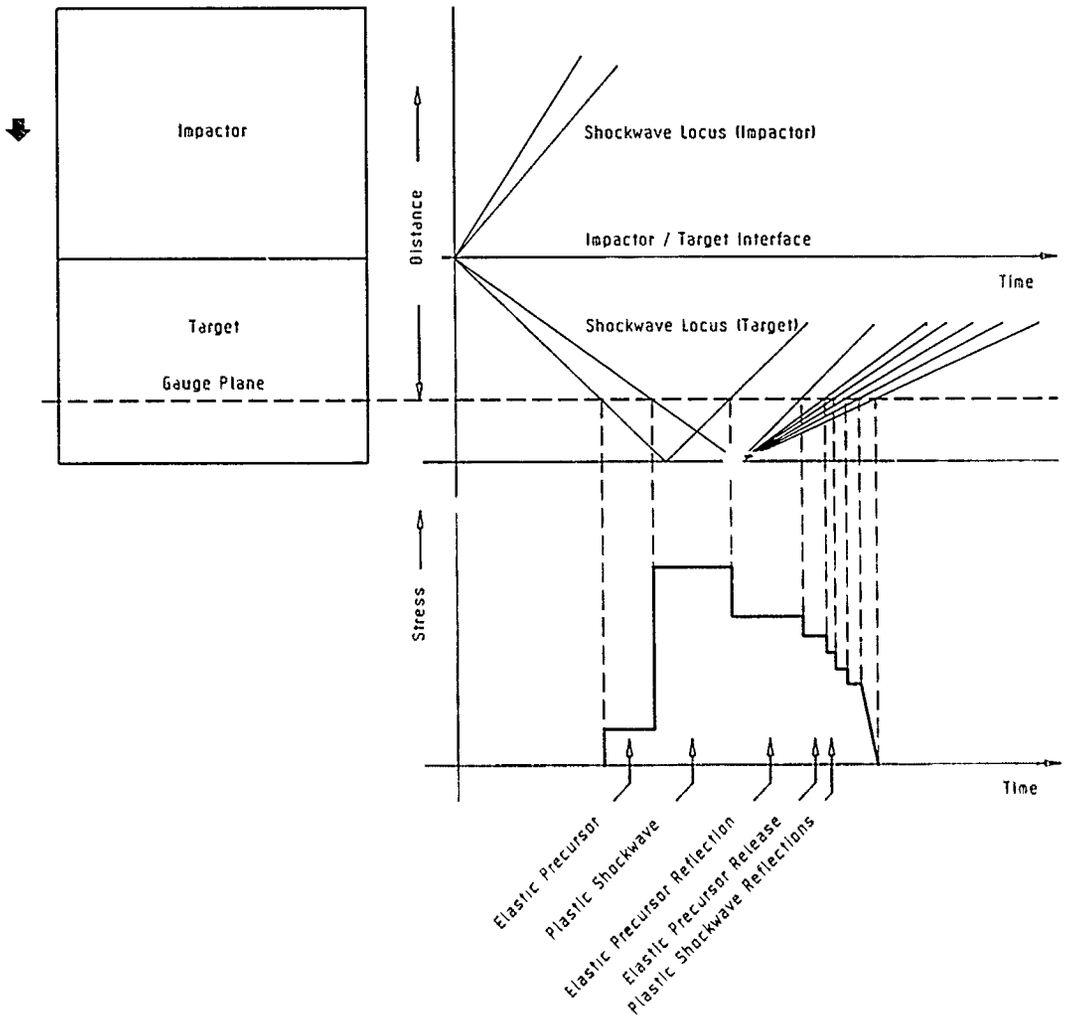


Figure 36 *Correlation of stress profile with shock wave interaction (Yaziv, Rosenberg and Partom 1980).*

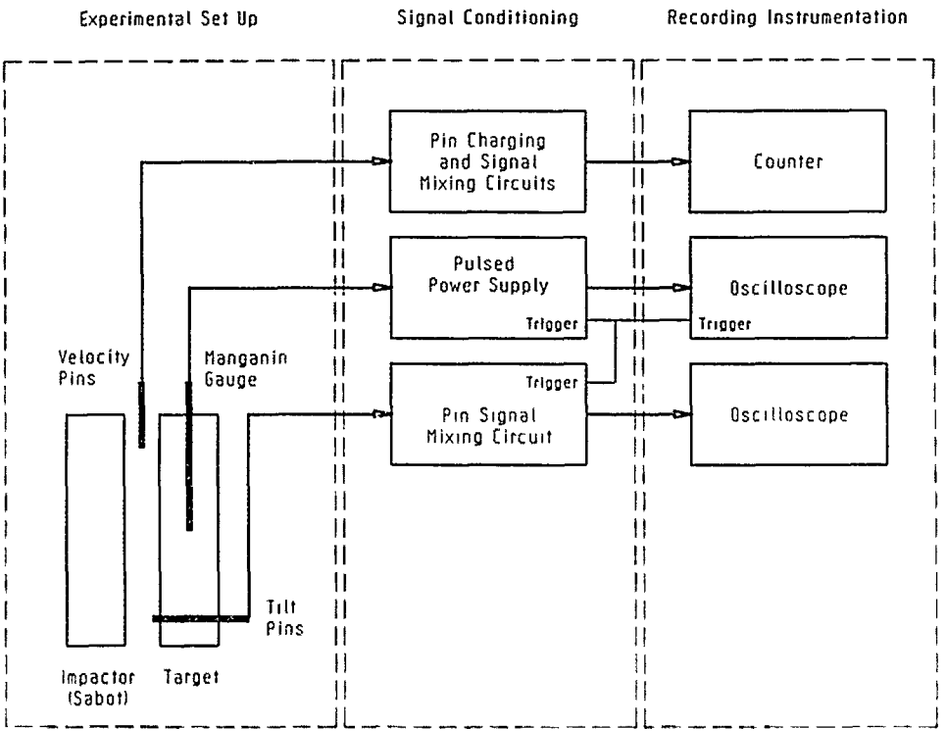


Figure 37 *Experimental set up for calibration of piezoresistance gauges (adapted from Horning and Isbell 1975).*

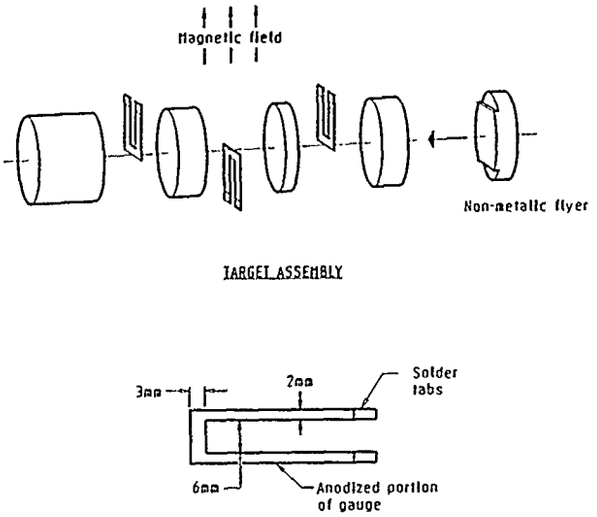


Figure 38 *Schematic diagram of Electromagnetic Velocity (EMV) gauge set up for measurements in explosives (Erickson et al 1981a).*

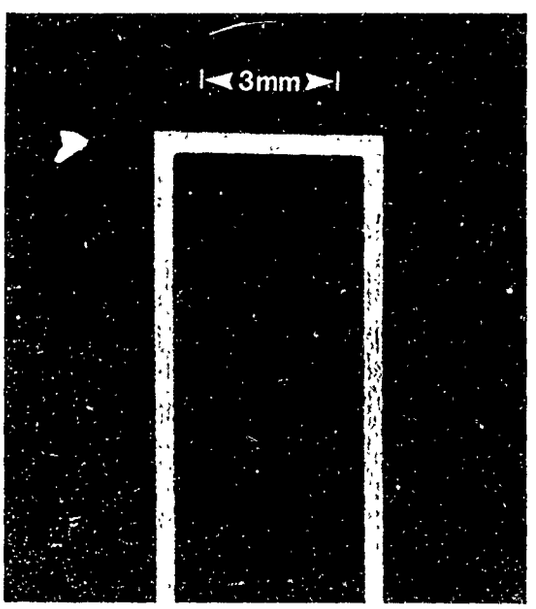


Figure 39 *Detail of Dynasen Inc. EMV gauge. The gauge consists of copper foil with polyimide insulation (not shown).*

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TITLE

A review of manganin gauge technology for measurements in the gigapascal range

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ABSTRACT

This report provides a comprehensive review of manganin gauge technology, including aspects of gauge design and construction, recording instrumentation and experimental techniques, and the interpretation of experimental results. Manganin gauges are shown to be capable of resolving to the order of 10 nanosecond pulses in the stress range 1 to 40 GPa.